Yet Another Model of Gamma-Ray Bursts

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ABSTRACT

Sari & Piran 1997a have demonstrated that the time structure of gamma-ray bursts must reflect the time structure of their energy release. A model which satisfies this condition uses the electrodynamic emission of energy by the magnetized rotating ring of dense matter left by neutron star coalescence; GRB are essentially fast, high field, differentially rotating pulsars. The energy densities are large enough that the power appears as an outflowing equilibrium pair plasma, which produces the burst by baryon entrainment and subsequent internal shocks. I estimate the magnetic field and characteristic time scale for its rearrangement, which determines the observed time structure of the burst. There may be quasi-periodic oscillations at the rotational frequencies, which are predicted to range up to 5770 Hz (in a local frame). This model is one of a general class of electrodynamic accretion models which includes the Blandford 1976 and Lovelace 1976 model of AGN, and which can also be applied to black hole X-ray sources of stellar mass. The apparent efficiency of nonthermal particle acceleration is predicted to be 10–50%, but higher values are possible if the underlying accretion flow is super-Eddington. Applications to high energy gamma-ray observations of AGN are briefly discussed.

Subject headings: Gamma Rays: Bursts — Stars: Neutron — Accretion: Accretion Disks — Galaxies: Active — Galaxies: Nuclei — Gamma Rays: Theory

1. Introduction

More than a hundred models of gamma-ray bursts (GRBs), including soft gamma repeaters (SGRs), have been published (Nemiroff 1994), yet there is at present no satisfactory and generally accepted model of GRBs. Even early data hinted at cosmological distances (Usov & Chibisov 1975, van den Bergh 1983). At these distances the inferred energy release of $\sim 10^{51}$ erg in a region constrained by their shortest observed times of variation implies (Cavallo & Rees 1978) the creation of an equilibrium pair and photon fireball with temperature $> 10^{10}\,^\circ$K.

The expected properties of radiation-pair fireballs (Goodman 1986) do not resemble the observed properties of GRB. Fireballs are expected to produce a brief (< 1 ms if their energy is released in a region of neutron star dimensions) pulse of black-body radiation, very different from the properties of observed (Fishman, *et al.* 1994) GRB, which have complex multipeaked time structure with durations in the range 10^{-2}–10^{3} s and nonthermal spectra.

For these reasons the hypotheses of cosmological distances and, by implication, of fireball models, were not generally accepted until data from BATSE made the geometrical case for them compelling (Meegan, *et al.* 1992, Piran 1992). This left the problem of reconciling the observed properties of GRB with the predicted properties of fireballs. Shemi & Piran 1990 had demonstrated that even a small contamination of the fireball with baryonic matter (and its associated non-annihilating electron excess) leads to the conversion of nearly all the fireball energy to the kinetic energy of a relativistic shell of baryons. Rees & Mészáros 1992 then pointed out that this shell could form a collisionless shock when it encountered surrounding diffuse matter, and suggested that radiation by the shocked matter could resolve the discrepancy between the predicted and observed properties. Relativistic shocks plausibly produce a nonthermal spectrum, optically thin at low frequencies (thus avoiding a Wien slope) and with power law extensions to higher frequencies. The complex temporal structure of GRB was attributed to the known complex spatial structure of diffuse matter, such as the interstellar medium. This suggestion was widely accepted (with a sigh of relief), and led to a great deal of work on the properties of fireballs and relativistic shocks.

Most fireball models of GRB have suggested that they are produced by the coalescence (Paczyński 1986, Eichler, *et al.* 1989) or formation (Dar, *et al.* 1992) of neutron stars. A fraction of the binding energy escapes as neutrinos and forms $e^{\pm}$ pairs by interactions between two neutrinos. These events release energy over several seconds, with a smooth time profile, as a consequence of the diffusion of neutrinos through matter dense enough to be opaque even to them (as demonstrated empirically by the duration of neutrino emission from SN 1987A). Katz & Canel 1996 pointed out that such a model could not explain short GRB, with durations < 2 s, and suggested collisions between two neutron stars, from which the escape of the neutrinos would be accelerated by the expansion of the debris. This argument is also applicable to the fine temporal substructure of long GRB, thus excluding processes depending on neutrino diffusion as the explanation of almost any GRB. The most popular version of this model involves the coalescence of two neutron stars, which has also been calculated (Davies, *et al.* 1994, Janka & Ruffert 1996, Mathews, *et al.* 1996) to be an inadequate source of neutrinos because coalescence is nearly adiabatic (the subsonic velocity of convergence does not make shocks) and does not sufficiently heat the cold degenerate neutron star matter.

Sari & Piran 1997a demonstrated, given quite general assumptions, that external shocks can only produce smooth, single peaked GRB, quite unlike observed GRB. This conclusion is very general because it is essentially geometrical; it does not depend on arguments concerning neutrino diffusion times or other microscopic physical processes. It is applicable to any single release of

energy, however thin the relativistic shell and however complex the distribution of surrounding matter, and therefore excludes even the brief (~ 5 ms) neutrino emission of colliding neutron stars as the explanation of GRB. They showed that a complex GRB pulse profile can only be the consequence of a complex history of energy release by the engine which powers the GRB. This excludes models in which the GRB energy is released in a single brief event, whether the coalescence, birth or collision of compact objects. It implies than models involving a continuous or intermittent wind (Paczyński 1986) are more likely to be correct that those involving a single fireball (Goodman 1986).

This paper proposes a resolution of these difficulties. As in much previous work, I begin with coalescing neutron stars which release an enormous ($\sim 3 \times 10^{53}$ ergs) amount of energy and which are estimated (Narayan, Piran & Shemi 1991, Phinney 1991) to occur at a rate consistent with the rate of GRB. Such a coalescence results in a rapidly differentially rotating object containing the mass of the two neutron stars. It is largely supported by internal pressure near its axis but more and more by angular momentum at larger distances from the axis. The central core may promptly collapse to a black hole, or may remain for an extended time as a rapidly differentially rotating neutron star, depending on the (uncertain) equation of state. It is surrounded by $\sim 0.1\ M_\odot$ of matter, at densities up to $\sim 10^{14}$ g/cm^3 but decreasing outwards, which is largely supported by angular momentum and which may be qualitatively described as an equatorial bulge or a thick accretion disc. For convenience and because this term is universally used I will refer to it as a disc, although it is unlikely to be strongly flattened. This configuration was described by Narayan, Paczyński, & Piran 1992, Usov 1992, Usov 1994, Thompson 1994. It is necessary to explain how it can produce the observed properties of GRB.

I propose that this rotating object produces a GRB by the electrodynamic processes which turn rotational energy into particle acceleration in pulsars. The required magnetic energy is only a tiny fraction of the GRB energy, and is much less than that required in order to explain GRB as the result of magnetic reconnection. In §2 I describe how these processes may work for parameters appropriate to GRB. In §3 I discuss the origin and estimate the magnitude of the magnetic field. The duration, rapidity of variation, and temporal complexity of GRB are discussed in §4, and possible quasi-periodic oscillations are predicted. I compare to magnetic field reconnection in §5. §6 considers GRB as members of a unified class of electrodynamically accreting objects which includes AGN and Galactic black hole X-ray sources (BHXS) such as Cyg X-1. §7 contains a summary and conclusions.

2. Electrodynamics

A rotating magnetized object is a source of energy. If it has a magnetic dipole moment misaligned with its rotation axis it radiates a power given by the classical magnetic dipole radiation formula. Goldreich & Julian 1969 showed that even an aligned rotor produces a similar power (in a relativistic wind) if the surrounding space is filled with plasma. In the present case the object is

differentially rotating, but that makes no essential difference; Blandford 1976 and Lovelace 1976 similarly applied the theory to differentially rotating accretion discs in order to explain AGN. For a large scale ordered magnetic field B a power

$$P_{rw} \sim \frac{B^2 r^6 \Omega^4}{2c^3} \tag{1}$$

flows outward in a relativistic wind, where Ω is the (approximately Keplerian) angular velocity and all parameters are roughly defined mass-weighted means over the disc. Only a fraction $\sim r\Omega/c$ of the magnetic field lines are open, so the power density on those field lines at the surface

$$S_{rw} \sim \frac{B^2}{8\pi} c \left(\frac{r\Omega}{c}\right)^3 . \tag{2}$$

Near the surface of a neutron star, or near the last stable circular orbit of a black hole, $r\Omega/c \sim 0.5$, so that S_{rw} is roughly an order of magnitude less than c times the magnetostatic energy density. Quite apart from uncertainties in the physical parameters, a nonrelativistic treatment is only approximate. For numerical evaluations I will take $(r\Omega/c)^3 = 0.1$.

The usual estimate of the power of a GRB at cosmological distances is $P \sim 10^{51}$ erg/s, although this is known at best to order of magnitude because their distances must be estimated from uncertain statistical arguments. Taking a radiating surface area of 10^{13} cm^2 (a neutron star or the inner disc around a black hole of a few $M_\odot$) implies $S \sim 10^{38}$ erg/cm^{2}s. If $S = S_{rw}$ then $B \sim 10^{15}$ gauss. This is much larger than known neutron star magnetic fields, but Thompson 1994 discussed the possibility that some neutron stars may be born with such fields (such neutron stars would be nearly unobservable as radio pulsars because of their rapid spindown). In §3 I discuss further the generation of magnetic fields of this magnitude as a consequence of neutron star coalescence.

In conventional pulsar models the magnetic field is accompanied (in an inertial frame) by an electric field $O(B\Omega r/c)$ (Goldreich & Julian 1969) which is large enough to pull charge from the stellar surface or to produce $e^\pm$ pairs by a process of vacuum sparking (Sturrock 1971, Ruderman & Sutherland 1975). In the GRB problem the electric fields are even larger than in pulsars (because of both the assumed larger B and the large Keplerian Ω in the inner disc), so there is no difficulty in providing the pair plasma which is necessary for the aligned rotor to produce power.

The power density is extremely large; $S_{rw} \sim 10^{38}$ erg/cm^{2}s corresponds to an effective temperature $k_B T_e \approx 3$ MeV. If $k_B T_e > 20$ KeV, corresponding to the much lower equilibrium energy density $E_{eq} \equiv aT_e^4 > 10^{19}$ erg/cm^3 and radiated power density $S_{eq} \equiv \sigma_{SB} T_e^4 > 10^{29}$ erg/cm^{2}s, the energy density is sufficiently large that an opaque equilibrium pair plasma can form (the temperature is found from the condition that the equilibrium pair density has a Thomson scattering mean free path ~ 1 km, but is very insensitive to this assumed length). The laws of thermodynamics permit this energy and power density to assume the form of a smaller number of more energetic particles, but interactions among them and with the magnetic field will generally lead to rapid equilibration. This is particularly true at higher energy densities, at which the

density of interacting particles is higher; the energy density required in GRB is $\sim 10^9$ times the minimum required for an equilibrium pair plasma, so it is safe to assume that it forms. The opaque pair plasma takes the place of the dilute transparent fluid of energetic particles found in radio pulsars, for which the power density is much smaller ($S \sim 10^{27}$ erg/cm^{2}s for the Crab pulsar, and less for others). Isolated neutron stars with sufficiently strong fields and rapid rotation that their power density exceeds S_{eq} (such as a newly born neutron star with a field like that of the Crab pulsar but a spin period < 3 ms) may resemble GRB of very long duration more than conventional radio pulsars.

An unknown amount of baryonic matter will be entrained by the outflowing pair plasma. The degree of entrainment and the pair density will vary across the surface of the disc, both in space and in time, as the magnetic field and flow geometry vary. There is abundant opportunity for radiation by internal shocks as these flows of varying Lorentz factors overtake each other and interact, as is required to explain the complex time structure of GRB.

The deposition of a super-Eddington power (for example, by viscous dissipation or neutrino transport) within the deep interior of the dense, massive disc need not imply a strong mass outflow. Hence pair plasmas with low baryon loading and high Lorentz factors are possible. The Eddington limit only constrains the rate at which radiation can diffuse through matter. A "super-Eddington" diffusive photon luminosity does not produce an outflowing wind; it does not occur in a hydrostatic configuration. If a power greater than the Eddington limit (but less than the binding energy divided by the hydrostatic relaxation time) is injected into opaque matter it will produce only a quasi-static structural relaxation; see Katz 1996 for a recent discussion.

The magnetic field inside the disc produces a stress which leads to an outward flow of angular momentum, and inward flow of mass and the release of gravitational energy, as in the usual theory of accretion discs. This process is usually described as dissipation by magnetic viscosity, and its detailed mechanism, as well as the process by which the energy released is thermalized, is controversial. The relevant component of magnetic stress (in a thin disc) is $B_r B_\phi/4\pi$. Regardless of the detailed mechanism of field production, no other magnetic stress is available to transport angular momentum outward. A Newtonian estimate for the power released by magnetic viscosity is then

$$P_{visc} \approx \frac{B_r B_\phi}{2} \Omega r^2 h, \tag{3}$$

where h is the disc half-thickness.

Comparing Equations (1) and (3) and assuming that the B^2 on the surface of the disc used in Equation (1) is comparable to $B_r B_\phi$ leads to

$$\frac{P_{rw}}{P_{visc}} \sim \frac{r}{h} \left(\frac{\Omega r}{c}\right)^3. \tag{4}$$

The ratio r/h is variously estimated at 1–10; $(\Omega r/c)^3 \sim 0.1$ near a neutron star's surface or a black hole's last stable circular orbit, but declines $\propto r^{-3/2}$ at larger radii. Hence near the surface

(or last stable circular orbit) the electrodynamic efficiency

$$\epsilon \equiv \frac{P_{rw}}{P_{rw} + P_{visc}} \tag{5}$$

is in the range 0.1–0.5, while it is small in the outer regions of a disc. The efficiency of production of nonthermal power (and ultimately radiation) does not depend on the magnitude of the magnetic field, although it does depend on the field geometry.

The energy available from the accretion of $0.1 M_\odot$ is $\sim 10^{53}$ ergs, assuming maximally rotating Kerr geometry, so that at least $\sim 10^{52}$ ergs are available for GRB emission. This is sufficient to explain the energetics of GRB at cosmological distances so long as the efficiency of emission by the relativistic shocks is not small. That portion of the accretional energy which does not appear in the relativistic wind is thermalized within the disc and either emitted as neutrinos or swept into the black hole (or onto the rotating neutron star) along with the accreted matter.

3. Magnetic Fields

Can magnetic fields of 10^{15} gauss be justified? When two neutron stars coalesce they quickly (in a time $\sim (R^3/GM)^{1/2} \sim 10^{-4}$ s) settle down to an axisymmetric but differentially rotating configuration. The near-adiabaticity of neutron star coalescence implies that thermal convection is weak. Because the flow is axisymmetric the Cowling theorem (Shu 1992) establishes that it cannot generate a magnetic field by a dynamo process. It is possible that a weak dynamo may occur because of small deviations from exact axisymmetry, but these cannot be estimated.

Differential rotation generates azimuthal field from radial field, requiring only that the field be frozen into the matter, according to the equation

$$\frac{dB_\phi}{dt} = B_r \frac{d\Omega}{d\ln r} \approx -\frac{3}{2} B_r \Omega. \tag{6}$$

This is not a dynamo, as the radial field is not regenerated, and will eventually decay resistively.

Ropes of (nearly azimuthal) magnetic flux are buoyant, and will rise to the surface of the disc on a time scale

$$t_b \sim \frac{h}{v_A} \sim \frac{h(4\pi\rho)^{1/2}}{B}, \tag{7}$$

where $v_A = B/(4\pi\rho)^{1/2}$ is the Alfvén speed and ρ a mean density (depending on the geometry, this may involve the Parker instability, but the time scale is determined by dimensional considerations alone). A rough (statistically) steady state will be reached when the rate of field growth (Equation 6) equals its rate of loss by buoyancy (Equation 7). Using the likely dominant component B_ϕ for B in Equation (7) permits its magnitude to be estimated. The result is

$$B_\phi \sim \left[\frac{3}{2} B_r \Omega h (4\pi\rho)^{1/2}\right]^{1/2} \sim 10^{15}\, B_{r13}^{1/2} \Omega_4^{1/2} h_6^{1/2} \rho_{13}^{1/4} \text{ gauss}, \tag{8}$$

where $B_{r13} \equiv B_r/(10^{13}\,\mathrm{gauss})$, $\Omega_4 \equiv \Omega/(10^4\,\mathrm{s}^{-1})$, $h_6 \equiv h/(10^6\,\mathrm{cm})$ and $\rho_{13} \equiv \rho/(10^{13}\,\mathrm{g\,cm}^{-3})$.

A plausible origin of B_r is the pre-coalescence magnetic fields of the neutron stars. Values as large as $\sim 10^{13}$ gauss are observed for some radio pulsars, justifying the use of $B \sim 10^{15}$ gauss if the Parker instability or buoyant rise convert B_ϕ to B_z with reasonable efficiency. The relative magnitudes of the three components B_r, B_ϕ and B_z are uncertain, which introduces similar uncertainties into estimates such as Eq. (4). Millisecond pulsars are observed with fields as small as $\sim 10^9$ gauss (other neutron stars may have yet smaller fields but be unobservable for that reason), implying $B \sim 10^{13}$ gauss.

4. Time Scales

4.1. Duration

The magnetic fields determine the rate of accretion and the rate of emission of GRB power. If B_z is comparable to the B_ϕ estimated from Eq. (8) then

$$P_{rw} \sim 10^{51}\, B_{r13}\Omega_4^5 h_6 \rho_{13}^{1/2} r_6^6 \text{ erg/s}, \tag{9}$$

where $r_6 \equiv r/(1.5 \times 10^6\,\mathrm{cm})$. A total GRB energy $E \sim 10^{51}$ ergs implies a duration, assuming efficient conversion of relativistic wind energy, of

$$t_d \sim 1\, B_{r13}^{-1}\Omega_4^{-5} h_6^{-1} \rho_{13}^{-1/2} r_6^{-6} \text{ s}. \tag{10}$$

Short GRB may be explained by the coalescence of neutron stars with magnetic fields roughly comparable to those observed for most radio pulsars. The shortest GRB ($t_d \sim 10^{-2}$ s) may require somewhat larger fields (not implausible, because pulsars with such large fields would spin down rapidly and have short observable lives), or somewhat different values of other parameters, or may instead be explained by smaller values of E and P_{rw}, consistent with our poor quantitative understanding of GRB energetics.

GRB with durations as long as $\sim 10^4$ s may be explained by the coalescence of millisecond pulsars with $B_r \sim 10^9$ gauss, and even longer durations (such as the $\sim 10^5$ s required to explain the "Gang of Four" apparent repetitions of October 27–29, 1996 as a single event; Meegan, *et al.* 1996, Connaughton, *et al.* 1997) are possible. In the present model long durations pose no intrinsic difficulty, and need not be associated with unusually soft spectra, in contrast to external shock models in which they imply low Lorentz factors and low radiative efficiency. Very long GRB are faint, on average, in any model in which the total energy of a GRB is limited, and are therefore difficult to detect; they may be more frequent than is apparent from intensity (or rate-of-rise) selected samples.

4.2. Time scales and substructure

In the present model the magnetic field rearranges itself on the time scale t_b, which may be rewritten

$$t_b \sim (4\pi\rho)^{1/4}\left(\frac{2h}{3B_r\Omega}\right)^{1/2} \sim 0.01\ h_6^{1/2}\rho_{13}^{1/4}B_{r13}^{-1/2}\Omega_4^{-1/2}\ \mathrm{s}. \tag{11}$$

Equivalently, B_r may be eliminated in favor of the duration $t_d \equiv E/P_{rw}$, yielding

$$t_b \sim \left(\frac{t_d}{2E}\right)^{1/2}(4\pi\rho)^{1/2}h^{3/2}r\Omega^{1/2} \sim 0.04\ \left(\frac{10^{51}\ \mathrm{erg\,s^{-1}}}{P_{rw}}\right)^{1/2}\rho_{13}^{1/2}h_6^{3/2}r_6\Omega_4^{1/2}\ \mathrm{s}. \tag{12}$$

The model predicts that the GRB intensity does not vary much on time scales shorter than t_b. This appears to be consistent with the data.

4.3. Complexity

The complex time structure of GRB is notorious. It led Stecker & Frost 1973 to point out a qualitative resemblance to the time structure of Solar flares. Many different qualitative forms are seen: continuous irregular fluctuations, isolated peaks separated by longer intervals with no detected emission, single simple peaks, peaks with numerous sub-peaks.... It is beyond the capability of any theoretical model to predict this complex structure; it is a formidable task even to construct suitable measures to describe it statistically.

In the present model the field rearranges itself on the time scale t_b, and there are $t_d/t_b \sim 10^2$–10^3 (the numerical value depending on poorly known parameters) rearrangements in a GRB of 10 s duration; note that t_d is the length of time during which the GRB radiates strongly, and may be much less than the measured pulse length if there are peaks of intensity separated by periods of much lower or zero emission. This permits a great variety of complex time structures. Their details depend on unknown details of the disc's magnetohydrodynamics. For comparison, consider the problem of explaining the Solar magnetic cycle. This is incompletely understood, even with the aid of a great body of data. Its observed complexity argues for the plausibility of obtaining the variety of GRB time structure as the result of disc magnetohydrodynamics.

The preceding is only an argument for the plausibility of obtaining the observed GRB temporal phenomenology. It is not a demonstration that the observed heterogeneity and complexity can be obtained. Nevertheless, the situation is better than for external shock models, which Sari & Piran 1997a showed could not explain the data. Even before their argument was made, external shock models depended on the hopeful wish that the temporal complexity of GRB could be attributed to the (also poorly understood) spatial complexity of the interstellar medium.

The failure to demonstrate that the variety of observed pulse forms must occur might be used as an argument against the present model. If it is accepted that all classical GRB are produced

by a single kind of event then this heterogeneity could be used equally as an argument against any model, because we have never understood any physical process which produces complex and heterogeneous pulse forms well enough to predict these forms. The alternative hypothesis that many different kinds of events produce GRB is even more unlikely: apart from the observed homogeneity among GRB in energy scale, spatial distribution, spectral properties and even the fact of complex pulse structure, this hypothesis requires the construction of several satisfactory models, when it is hard enough to find even one! All that can be asked is that a model *permit* temporal complexity and heterogeneity.

4.4. Quasiperiodic oscillations

The magnetic field of the accretion disc will not, in general, be axisymmetric. If the deviation from axisymmetry is large the resulting model resembles magnetic dipole emission (though of a relativistic wind rather than of an electromagnetic wave) more closely than an axisymmetric rotator; Equations (1) and (2) remain valid in either case. The particle flux and the observed radiation may therefore be modulated at the rotation frequency, which varies with r in the disc. This time dependence will be convolved with the time dependence of acceleration and radiation of the radiating particles and geometric delays arising from a range of signal path lengths (Ruderman 1975, Katz 1994), and may thereby be unobservable. However, the acceleration and radiation times may be short (Katz 1994, Sari, Narayan & Piran 1996, Sari & Piran 1997b), and the rotational modulation should be looked for in gamma-ray data of sufficiently high temporal resolution. It is also conceivable, though probably unlikely, that sufficient coherent emission occurs to produce a detectable signal at radio frequencies, as in radio pulsars.

The expected signal would consist of quasi-periodic oscillations (QPO). There is predicted to be a high frequency cutoff at the maximum rotational frequency of the disc. For a disc surrounding a maximally rotating Kerr black hole of 2.8 $M_\odot$ (the expected result of the coalescence of two neutron stars) the frequency in the source frame of the last stable circular orbit (Shapiro & Teukolsky 1983) is 5770 Hz. If QPOs with an upper frequency cutoff below this value are observed, cosmological distances will be verified and the redshifts of individual GRB measured. The maximal rotational frequency of a differentially rotating neutron star depends on its distribution of angular momentum and is significantly smaller. It might be calculable from simulations of neutron star coalescence, but the interpretation of the data would be more ambiguous.

The spectral power density will drop off towards lower frequencies because both the energy release and the relativistic wind efficiency (Equation 5) decline with r (a naive estimate is that the power density varies $\propto \Omega^{2/3}$). Discs resulting from neutron star coalescence may have an abrupt outer edge, because viscosity has not had time to extend them to large radii or because exothermic nuclear reactions in expanded neutronized material expel their lower density regions, so that there may also be an abrupt low frequency cutoff. The distribution of power will give some indication of the radial structure and distribution of magnetic fields in the disc.

5. Magnetic Reconnection

It was natural (Stecker & Frost 1973, Katz 1982, Narayan, Paczyński, & Piran 1992, Katz 1994) to consider magnetic field reconnection as the explanation of the complex time structure of GRB. This is unlikely. It would require that the entire GRB energy (divided by an efficiency < 1) pass through the form of magnetic energy. This would require a strong dynamo, but we expect any dynamo to be weak (if present at all) because the flow is axisymmetric, at least to a first approximation.

The mechanism proposed in this paper has the advantage (in comparison to magnetic reconnection) that the same magnetic flux is a source of emitted power for an indefinite time. Even a small (compared to the accretion energy) magnetic energy can be the conduit through which the entire GRB energy flows (because a GRB is very long compared to r/c). In contrast, in a magnetic annihilation model the magnetic energy must be regenerated rapidly by a dynamo, and all the radiated energy must have at one time assumed the form of magnetostatic energy.

The relativistic wind has a power (Equation 2) which is the magnetic energy multiplied by a speed $O(r^3\Omega^3/c^2) \sim O(c/10)$. In order to be equally powerful, magnetic annihilation would have to act on a surface covering most of the inner accretion disc, throughout the duration of a GRB, with a reconnection speed $v_f \sim c/10$. This is surely optimistic. In general, v_f must be less than v_A, which is small in dense matter (§3) although it may be relativistic where the wind is generated.

Any process which produces the observed power density produces an equilibrium pair plasma, as discussed in §2. The electrical conductivity of such a plasma

$$\sigma \sim \frac{m_e c^3}{e^2} \sim 10^{23}\ \mathrm{s}^{-1}, \tag{13}$$

as may be found by dimensional analysis or by estimating the number of charge carriers and their scatterers (charged particles and photons). The conductivity is approximately independent of temperature for $k_B T > m_e c^2$ because the densities of carriers and of scatterers each vary $\propto T^3$. The relativistic temperature makes counterstreaming plasma instabilities unlikely, and their high density makes the relative drift velocity of electrons and positrons small.

In a reconnecting current sheet of thickness ℓ the time ℓ/v_f required for the flow to regenerate the magnetic flux may be equated to the resistive dissipation time $\sigma\ell^2/c^2$. The result is

$$\ell \sim \frac{c^2}{v_f \sigma} \sim \frac{c}{v_f}\frac{e^2}{m_e c^2} \sim \frac{c}{v_f} r_e, \tag{14}$$

where $r_e \equiv e^2/m_e c^2 = 2.82 \times 10^{-13}$ cm is the classical electron radius. The electron density at $k_B T \sim m_e c^2$ is $n_e \sim m_e^3 c^3/\hbar^3 \sim 10^{31}\ \mathrm{cm}^{-3}$. The discreteness of the charge carriers limits $\ell > n_e^{-1/3} \sim \hbar/(m_e c) \sim 4 \times 10^{-11}$ cm. This is consistent with Equation (14) only if

$$\frac{v_f}{c} < \frac{e^2}{\hbar c} \approx \frac{1}{137}. \tag{15}$$

This is a general limit on the speed of magnetic reconnection in a relativistic pair plasma. In the inner region of a disc around a black hole or a neutron star magnetic reconnection is, at best, an order of magnitude less powerful than the relativistic wind flowing on open field lines. Magnetic flux is probably destroyed by accretion onto the black hole or advection to infinity in the wind, rather than by reconnection.

6. Unified Model of GRB, AGN and BHXS

These three classes of objects have certain qualitative similarities (assuming the present model of GRB), despite large quantitative differences in their luminosities, masses, and time scales. They all are powered by accretion onto a central black hole. They all produce nonthermal radiation. They all show evidence for relativistic beaming and relativistic bulk motion. They all fluctuate irregularly in intensity. These similarities suggest that it may be possible to construct a single unified model for them all. The present model for GRB resembles the Blandford 1976, Lovelace 1976 model for AGN, although they assumed (probably unnecessarily) that the magnetic dipole moment was aligned with the rotational axis. These models may be scaled to stellar mass BHXS such as Cyg X-1. The most important difference is that in GRB the relativistic wind is thermalized to an equilibrium pair plasma, while at the lower power densities of AGN and BHXS it remains transparent and nonequilibrium.

I consider a class of models of AGN and BHXS in which the electromagnetic energy is converted to the energy of accelerated particles close to the black hole. Very energetic particles take the place of the equilibrium pair plasma in GRB. In another class of models of AGN and BHXS the disc radiates vacuum electromagnetic waves instead of energetic particles. At much greater radii these waves accelerate particles, just as in GRB the pair plasma accelerates particles in distant shocks. These two classes of models can be comparably efficient particle accelerators. I do not consider the vacuum wave model further because it is less closely analogous to the GRB model (which cannot be a vacuum wave model because the energy density leads to creation of an equilibrium pair plasma), and because external plasma injection or pair breakdown (§6.7) are likely to fill the wave zone with energetic particles

6.1. Nonthermal efficiency

All three classes of objects show a significant amount of nonthermal emission. In GRB all the observed emission appears to be nonthermal, although it is not the primary radiation emitted by the central engine but rather the consequence of a shock produced by or in the relativistic outflow; the high energy density at the source thermalizes the relativistic wind. Still, the wind is produced by a fundamentally nonthermal process. In many AGN a substantial fraction of the power appears as nonthermal visible synchrotron radiation or high energy gamma-rays. Extragalactic radio

sources appear to be the consequence of the acceleration of relativistic particles in AGN. The case for nonthermal emission in BHXS is plausible but less compelling. It is a natural explanation of the complex multi-component spectra observed for the best studied example (Cyg X-1). The superluminal radio components and jets observed in some of these objects certainly require acceleration of relativistic particles. Cyg X-3 also shows strong outbursts of nonthermal radio emission, although there is no direct evidence it contains a black hole.

In GRB the efficiency ϵ (Equation 5) is not directly measured because virtually all the thermal radiation emerges as neutrinos and is essentially undetectable. For the lower density accretion flows of AGN and BHXS neutrino emission is negligible, and the thermal radiation produced by viscous heating is directly observable. In §2 I argued that $\epsilon \sim 0.1$–0.5 is likely, independent of the magnitude of the magnetic field (but depending on its unknown orientation and spatial structure). This is consistent with observations of AGN; the likelihood of relativistic beaming precludes quantitative comparisons. This range of ϵ is also consistent with observations of Cyg X-1 and other BHXS if the harder components of their spectra are either nonthermal or the thermal emission of optically thin matter heated by nonthermal particles.

The measured nonthermal efficiency is also affected by radiation trapping (Katz 1977); if the mass accretion rate exceeds the nominal Eddington rate the excess mass is swallowed by the black hole, but the emergent luminosity (in thermal radiation which diffuses through the accretion flow) is limited to slightly less than L_E (Eggum, Coroniti & Katz 1988). An analogous limit applies to the unobserved neutrino luminosity. In AGN and BHXS this can lead to an apparent nonthermal efficiency $\epsilon \to 1$ and $P_{rw} \gg L_{th}$, because the nonthermal wind luminosity is proportional to the accretion rate and is not subject to the Eddington limit, while the emergent thermal luminosity L_{th} cannot exceed L_E even if $P_{visc} \gg L_E$.

6.2. Time structure

Substitution of elementary estimates of steady nonrelativistic accretion discs (the GRB disc may be steady on the fastest time scale r/c, even though it is unsteady on the timescale t_b) into Equation (12) yields

$$t_b \sim \frac{r}{c(\alpha\epsilon_a)^{1/2}}, \tag{16}$$

where α is the conventional ratio of viscous stress to pressure and $\epsilon_a c^2$ is the energy per unit mass released by accretion. For $\alpha = 0.1$ (much larger than implied for GRB) and $\epsilon_a = 0.06$ (appropriate to the last stable circular orbit around a Schwarzschild black hole)

$$t_b \sim 4 \times 10^{-4} \frac{M}{M_\odot} \text{ s}. \tag{17}$$

This estimate is roughly an order of magnitude longer, but has the same scaling, as the most naive estimate of $\sim r/c$. For a maximally rotating Kerr black hole the corresponding estimate is

$$t_b \sim 2 \times 10^{-5} \frac{M}{M_\odot} \text{ s}, \tag{18}$$

comparable to the naive estimate.

In comparing to AGN it should be remembered that the nonthermal power is not Eddington limited, nor is the thermal radiation of unbound gas clouds heated by the nonthermal power; the black hole's mass therefore cannot be estimated from the luminosity, but only from its direct gravitational influence on surrounding matter. The matter in such clouds is driven away by radiation pressure, and must be resupplied, for example by the infall and disruption of stars (the infall of opaque stars is an illustration of the principle that there is no Eddington bound on the rate of mass accretion).

The complex multi-state behavior of Cyg X-1 may qualitatively be attributed to changes in the magnetic geometry, which affect ϵ, but the magnetic cycles of accretion discs are too poorly understood to admit a more quantitative understanding. There is some resemblance between the irregular multi-peaked structure of GRB and the appearance and disappearance of hard components in the spectrum of Cyg X-1. Even in a thermal model, these hard components require the presence of matter much hotter than black body equilibrium temperatures (which are < 1 KeV), and this matter may be heated by the nonthermal particles.

It is interesting to note a qualitative similarity between BHXS and GRB. In one BHXS (Cyg X-1; Weiskopf, *et al.* 1978) a non-zero time skewness was measured from an X-ray time series. Time skewness of the same sense is obvious in many GRB, where it is often called the FRED (fast rise, exponential decay) pulse shape. Searches for time skewness in AGN time series have so far been unsuccessful (Press & Rybicki 1997), but do not exclude it.

6.3. Particle acceleration

Pulsars and GRB (in the present model) have large electric fields which lead to pair production. A supermassive black hole in a galactic nucleus, or a stellar mass black hole in a mass transfer binary, is surrounded by a complex accretional gas flow. Significant sources of mass include the companion star (in the BHXS), the galactic interstellar medium (in the AGN) and the surface of the outer parts of the accretion disc. Although the flow is not understood in detail, it is plausible that some of this gas has sufficiently little angular momentum (or loses its angular momentum at large radii) to permit accretion on the axis of rotation, and can fill all directions around the black hole (as was found in the calculations of Eggum, Coroniti & Katz 1988). A pulsar-like vacuum is not likely. The space charge density required to neutralize the corotational electric field (Goldreich & Julian 1969) is small, and may readily be supplied by this plasma. Pair

production is therefore not required for the extraction of energy from the rotating disc in AGN and BHXS, although it may occur.

Near a luminous object accelerated electrons and positrons would be rapidly slowed by Compton scattering on the thermal radiation field (Jones 1965, Katz & Salpeter 1974); the energy loss length ℓ_C of an electron with Lorentz factor γ in an isotropic radiation field of intensity $L_{th}/(4\pi r^2)$ near a mass M, assuming the Thomson cross-section, is

$$\ell_C = \frac{m_e}{m_p}\frac{1}{\gamma}\frac{L_E}{L_{th}}\frac{rc^2}{GM}r, \tag{19}$$

The first two factors are each $\ll 1$, and the last two are not much greater than unity in the inner disc of a luminous object, so that $\ell_C \ll r$. This result is also approximately valid for anisotropic radiation fields, except in the extreme case of a particle moving accurately in the direction of a narrowly collimated beam of radiation.

Given a value for B, it is possible to calculate the maximum energy an electron achieves, and to estimate its radiation. Equating the magnetic stress to that required to supply a bolometric luminosity L_b (including relativistic wind, thermal radiation and radiation advected into the black hole) yields

$$\frac{B^2}{8\pi} \sim \frac{1}{2}\frac{L_b}{L_E}\left(\frac{GM}{rc^2}\right)^{3/2}\frac{r}{h}\frac{c^4}{GM\kappa} \sim 3\times 10^7\ \frac{L_b}{L_E}\left(\frac{10GM}{rc^2}\right)^{3/2}\ \frac{r}{10h}\frac{10^8 M_\odot}{M}\ \frac{\mathrm{erg}}{\mathrm{cm}^3}, \tag{20}$$

where κ is the Thomson scattering opacity. This estimate assumes only that the viscosity is magnetic and that $B^2 \sim \langle B_r B_\phi\rangle$; it is not dependent on an assumption of equipartition or on any theory of α, and is derived from the accretion rate implied by L_b alone.

Equating the energy gained in a length ℓ_C to the energy $m_e c^2\gamma$ lost by Compton scattering, using Equation (19), yields the maximum Lorentz factor

$$\gamma_C \sim \left(\frac{eEr}{m_p c^2}\frac{rc^2}{GM}\frac{L_E}{L_{th}}\right)^{1/2}. \tag{21}$$

Using $E \sim vB/c \sim B(GM/rc^2)^{1/2}$ and Equation (20) yields

$$\begin{aligned}\gamma_C &\sim \left(\frac{rc^2}{GM}\right)^{1/8}\left(\frac{L_{th}}{L_E}\right)^{-1/2}\left(\frac{r}{h}\right)^{1/4}\left(\frac{GNm_e^2}{e^2}\right)^{1/4}\left(\frac{L_b}{L_E}\right)^{1/4}\\ &\sim 1.0\times 10^4\left(\frac{M}{M_\odot}\right)^{1/4}\left(\frac{rc^2}{10GM}\right)^{1/8}\left(\frac{L_{th}}{L_E}\right)^{-1/2}\left(\frac{r}{10h}\right)^{1/4}\left(\frac{L_b}{L_E}\right)^{1/4},\end{aligned} \tag{22}$$

where $N \approx 1.2\times 10^{57}\, M/M_\odot$ is the ratio of the black hole mass to the proton mass. It is amusing to express γ_C in terms of fundamental constants, dropping factors of order unity which depend on the properties of the individual object, and noting that for a Chandrasekhar mass M_{Ch} $N \approx (\hbar c/Gm_p^2)^{3/2}$:

$$\gamma_C \sim \left(\frac{m_e}{m_p}\right)^{1/2}\left(\frac{e^2}{\hbar c}\right)^{-1/4}\left(\frac{Gm_p^2}{\hbar c}\right)^{-1/8}\left(\frac{M}{M_{Ch}}\right)^{1/4}. \tag{23}$$

6.4. Compton gamma-rays

Equation (22) directly gives an upper bound on the Compton scattered photon energy $\gamma_C m_e c^2$, which is $\sim 10^{12}$ eV for typical AGN parameters and $\sim 10^{10}$ eV for typical BHXS parameters. This explains, at least qualitatively, the production of TeV gamma-rays in AGN such as Mrk 421 (Gaidos, *et al.* 1996) and Mrk 501 (Quinn, *et al.* 1996).

The actual spectral cutoff depends on the spectrum of thermal photons; if their energy $\hbar\omega_{th} \sim m_e c^2/\gamma_C$ the cutoff will be $\sim \gamma_C m_e c^2$; if $\hbar\omega_{th} < m_e c^2/\gamma_C$ the cutoff will be $\sim \gamma_C^2 \hbar\omega_{th}$; if $\hbar\omega_{th} > m_e c^2/\gamma_C$ the cutoff is $\sim \gamma_C m_e c^2$ but Equation (22) then underestimates γ_C because of the reduction in Klein-Nishina cross-section and the discreteness of the energy loss. The observed spectra of AGN and BHXS are so complicated (it is also unclear which components are emitted at the small radii at which electron acceleration is assumed to occur) that it is difficult to be quantitative. Visible radiation from AGN and soft X-rays from BHXS place Compton scattering marginally in the Klein-Nishina range (note that both the black body $\hbar\omega_{th}$ and $m_e c^2/\gamma_C$ scale $\propto M^{-1/4}$), but quantitative estimates depend on the unknown factors in parentheses in Equation (22).

Because the Compton scattering power of an electron and the frequency of the scattered photon each are proportional to γ^2, while the rate of energy gain in an electric field is independent of γ, there is expected to be a broad peak in νF_ν around the cutoff frequency, with $F_\nu \propto \nu^{1/2}$ at lower frequencies (the same slope as for synchrotron radiation, for the same reasons). In principle, the weak dependence of γ_C on M, L_{th} and L_b in Equation (22) could be tested if M were estimated independently of the luminosities, for example, from the time scale of variations.

The majority of the power which goes into electron acceleration may appear as Compton scattered gamma-rays of energy $\sim \gamma_C m_e c^2$. This is half P_{rw} in a proton-electron wind and all of P_{rw} if pairs are accelerated. As discussed in §6.1 this can far exceed L_{th} if the disc is undergoing highly supercritical accretion. This may explain the dominance of the emitted power by energetic gamma-rays in some AGN. Supercritical accretion by black holes of comparatively low mass also permits more rapid variability than accretion at the Eddington limit.

6.5. Synchrotron radiation

Electrons with Lorentz factors up to that given by Equation (22) may radiate synchrotron radiation, assuming an isotropic distribution of pitch angles, at frequencies up to

$$\nu_{synch} \sim \left(\frac{3}{8\pi^2}\right)^{1/2} \left(\frac{GM}{rc^2}\right)^{1/2} \frac{L_b}{L_{th}} \frac{r}{h} \frac{m_e c^3}{e^2} \sim 7 \times 10^{22} \frac{L_b}{L_{th}} \left(\frac{10GM}{rc^2}\right)^{1/2} \frac{r}{10h} \text{ Hz.} \tag{24}$$

The predicted spectral index for $\nu < \nu_{synch}$ is $-1/2$, because a uniform accelerating electric field produces a particle distribution function with energy exponent zero.

Unlike the Compton cutoff, the synchrotron cutoff is independent of the mass of the black hole. Because the magnetic and thermal photon energy densities may be comparable, synchrotron radiation may be energetically important. The ratio of synchrotron to Compton scattering powers, assuming an isotropic electron distribution, is the ratio of the magnetic to the thermal energy densities U_B/U_{th}:

$$\frac{P_{synch}}{P_{Compt}} = \frac{U_B}{U_{th}} \sim \frac{1}{2}\frac{L_b}{L_{th}}\frac{r}{h}\left(\frac{GM}{rc^2}\right)^{-1/2}. \tag{25}$$

Equations (24) and (25) suggest the possibility of synchrotron radiation with significant power up to $\sim$ GeV energies. In most circumstances this is probably a great overestimate because electrons may be effectively accelerated only parallel to the magnetic field—a component of E perpendicular to B does not effectively accelerate charged particles unless it varies at their cyclotron frequency, unlike the nearly steady corotational electric field.

Internal shocks in the relativistic wind may be as essential to radiation in AGN as in GRB, for in them plasma turbulence may partially isotropize the electron distribution, making effective synchrotron radiation possible. If the pitch angles remain small the frequency of synchrotron radiation is reduced and it is emitted nearly parallel to the direction of the electrons' motion, the magnetic field, and the Compton scattered gamma-rays. This can be described as relativistic bulk motion of the electrons and their associated radiation field, and may be necessary to avoid absorption of the photons by $\gamma - \gamma$ pair production.

6.6. Curvature radiation

The electrons also radiate curvature radiation (on the magnetic field lines of radii of curvature $\sim r$ at frequencies up to

$$\begin{aligned}\nu_{curv} &\sim \frac{1}{2\pi}\left(\frac{GM}{rc^2}\right)^{5/8}\left(\frac{L_{th}}{L_E}\right)^{-3/2}\left(\frac{L_b}{L_E}\right)^{3/4}\left(\frac{r}{h}\right)^{3/4}\frac{m_e^{3/2}c^3}{m_p^{3/4}e^{3/2}(GM)^{1/4}} \\ &\sim 3\times 10^{15}\left(\frac{10GM}{rc^2}\right)^{5/8}\left(\frac{L_{th}}{L_E}\right)^{-3/2}\left(\frac{L_b}{L_E}\right)^{3/4}\left(\frac{r}{10h}\right)^{3/4}\left(\frac{M_\odot}{M}\right)^{1/4}\ \mathrm{Hz}. \end{aligned}\tag{26}$$

Curvature radiation is insignificant, and its power is small. Unlike in pulsars, it cannot cause pair production because the electron Lorentz factor is limited by Compton scattering.

6.7. Pair production

The most energetic gamma-rays of energy E_γ may produce electron-positron pairs by interacting with the thermal photons. The condition for this to occur (assuming an isotropic thermal radiation field)

$$E_\gamma \hbar\omega_{th} \sim \gamma_C m_e c^2 \hbar\omega_{th} > (m_e c^2)^2, \tag{27}$$

is equivalent to the condition for the breakdown of the Thomson approximation to Compton scattering. It appears to be met in AGN and BHXS, taking the observed thermal spectra and assuming all factors in parentheses in Equation (22), except that involving the mass, are $O(1)$. If the thermal radiation field is assumed to be a black body then Equation (27) can be rewritten

$$\left(\frac{GM}{rc^2}\right)^{3/8}\left(\frac{r}{h}\right)^{1/4}\left(\frac{L_b}{L_{th}}\right)^{1/4}\left(\frac{e^2}{\hbar c}\right)^{-3/4} > 1. \tag{28}$$

It is clear that this condition is generally met; if (as is likely) the thermal spectrum is harder than a black body at the effective temperature the inequality holds even more strongly. Pair production by interaction between gamma-rays produced by Compton scattering of the accelerated electrons and thermal photons takes the place of pair production by curvature radiation which occurs in pulsars.

6.8. Proton acceleration

If there were no pair production, the accelerated plasma would consist of protons (and nuclei) and electrons. Even in the presence of pair production, protons may be accelerated along with the positrons. This is important in intense sources of thermal radiation, such as BHXS and AGN, because proton-photon scattering is negligible below the pion production threshold. Even above threshold, the effective energy loss cross-section (Greisen 1966) is a fraction $f \sim 10^{-4}$ of the Thomson cross-section. This permits accretion discs around black holes in AGN and BHXS to be efficient proton accelerators (as has previously been discussed by Lynden-Bell 1969, Kazanas & Ellison 1986, Katz 1991 in other models). Very high energy gamma-rays may then result from photoproduction of π^0 on thermal radiation. Collisions of protons with nucleons also produce high energy radiation directly from π^0 and indirectly by Compton scattering of the very energetic $e^\pm$ produced by $\pi^\pm \rightarrow \mu^\pm \rightarrow e^\pm$ (Katz 1991, Dar & Laor 1997).

The energy loss length of a proton is, in analogy to Equation (19),

$$\ell_p \approx \frac{1}{\gamma f}\frac{L_E}{L_{th}}\frac{rc^2}{GM}r. \tag{29}$$

Unlike Thomson scattering, this process has an energy threshold because of the π^0 rest mass of 135 MeV. If the thermal spectrum consists of visible light, the acceleration of protons is not restrained until $\gamma_p \sim 10^8$. The result analogous to Equation (22) is

$$\begin{aligned}\gamma_p &\sim \left(\frac{rc^2}{GM}\right)^{1/8}\left(\frac{L_{th}}{L_E}\right)^{-1/2}\left(\frac{r}{h}\right)^{1/4}\left(\frac{GNm_e^2}{e^2}\right)^{1/4}\left(\frac{L_b}{L_E}\right)^{1/4} f^{-1/2} \\ &\sim 1.0\times 10^6 \left(\frac{M}{M_\odot}\right)^{1/4}\left(\frac{rc^2}{10GM}\right)^{1/8}\left(\frac{L_{th}}{L_E}\right)^{-1/2}\left(\frac{r}{10h}\right)^{1/4}\left(\frac{L_b}{L_E}\right)^{1/4}.\end{aligned} \tag{30}$$

For an AGN with $M \sim 10^8 M_\odot$ this yields a limiting $\gamma_p \sim 10^8$, approximately the threshold at which π^0 photoproduction begins. As for pair production, γ_p and the thermal photon energy scale reciprocally with M, so that Equation (30) is (barely) applicable at all M.

The accelerated protons are not energetic enough to explain the highest energy cosmic rays, even though the nominal potential drop across the disc may approach $\sim 10^{20}$ eV for discs around supermassive black holes. The possible $\sim 10^{17}$ eV protons in AGN would produce $\sim 10^{16}$ eV photons, but these are not observable at great distances because of pair production on the microwave background radiation. In BHXS the corresponding photon energy is $\sim 10^{14}$ eV.

6.9. Quasiperiodic oscillations

AGN may show QPO, just as suggested for GRB, but with typical periods of order hours to days, depending on their masses in an elementary way (Equations 16–18). No such QPO have been found in the extensive body of visible light data on AGN. This may be explained if the visible light is produced far from the central object or by thermal radiation from a disc, which may be nearly azimuthally symmetric. It may be more fruitful (though more difficult observationally) to search for QPO in the energetic gamma-rays produced as particles are accelerated along magnetic field lines closer to the rotating disc, which would be expected to show the greatest deviations from axisymmetry, as in pulsars.

7. Discussion

The demonstration by Sari & Piran 1997a that the complex time structure of GRB must be intrinsic to their energy source has forced the rejection of most previous models. I have here outlined a model which may solve this problem. It predicts a minimum time scale of variations and suggests that QPO of predictable frequency may be observable. Observation of the predicted QPO would be strong evidence in favor of the model and would (given the assumed Kerr black holes) immediately reveal the redshift. Alternatively, if an identification with a galaxy of measurable redshift were made, a known function of the mass and angular momentum of the black hole would be determined, constraining theories of neutron star coalescence.

The development of the GRB model suggests that they result from the same process, disc accretion onto a black hole, believed to power AGN and Galactic BHXS. The parameter regimes are very different, but these diverse objects may all be the consequence of electrodynamic energy extraction from accretion discs. This leads to a unified model which, by emphasizing their similarities, may help explain all these phenomena.

GRB have a bimodal distribution of durations (Kouveliotou, *et al.* 1993), and long and short GRB appear to have different spatial distributions (Katz & Canel 1996) and may represent

different populations of objects. The distribution of magnetic fields of neutron stars appears also to be bimodal (although there are strong observational selection effects which are difficult to compensate for), which may offer a natural explanation. One class of pulsars and rotationally modulated accreting neutron stars has longer periods and $B \sim 10^{12}$ gauss; these may be the origin of short GRB. Lower field ($B \sim 10^9$ gauss) neutron stars form a second class, and are observed as millisecond pulsars and as the presumed low-field neutron stars in unpulsed low mass X-ray binaries (whose rapid rotation may be inferred from their QPO); these may be the origin of long GRB. High field neutron stars are produced with large impulses (as inferred from the space velocities of slow radio pulsars), and low field neutron stars (at least, millisecond pulsars found in globular clusters) are produced with low impulses (Katz 1975). This implies that if accurate enough coordinates could be obtained (Katz 1997) short GRB would be found to be further, on average, from the places of their birth (plausibly the discs of their host galaxies) than long GRB.

The coalescence of a neutron star and a black hole may produce a different event than the coalescence of two neutron stars, but it is not obvious what the qualitative observable differences would be. Similarly, the "silent" collapse of a rapidly rotating degenerate dwarf may produce a similar configuration to neutron star coalescence, though of half the mass, but known degenerate dwarf spins are too slow.

I thank T. Piran and R. Sari for discussions, Washington University for the grant of sabbatical leave, the Hebrew University for hospitality and a Forchheimer Fellowship, and NASA NAG 52682 and NSF AST 94-16904 for support.

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